12.3 The Bohr Atom and Beyond

The new discoveries in quantum theory revealed phenomena that can be observed on the scale of subatomic particles, but are undetectable on a larger scale. These discoveries gave physicists the tools they needed to probe the structure of atoms in much more detail than ever before. The refinement of atomic theory grew side by side with the development of quantum theory.

SECTION EXPECTATIONS

- Describe and explain the Bohr model of the hydrogen atom.
- Collect and interpret experimental data in support of Bohr's model of the atom.
- Outline the historical development of scientific models from Bohr's model of the hydrogen atom to present-day theories of atomic structure.
- Describe how the development of quantum theory has led to technological advances such as lasers.

KEY TERMS

- nuclear model
- Balmer series
- Rydberg constant
- Bohr radius
- principal quantum number
- Zeeman effect
- Schrödinger wave equation
- wave function
- orbital
- orbital quantum number
- magnetic quantum number
- spin quantum number
- Pauli exclusion principle
- ground state

Atomic Theory before Bohr

As you have learned in previous science courses, the first significant theory of the atom was proposed by John Dalton (1766–1844) in 1808. Dalton's model could be called the "billiard ball model" because he pictured atoms as solid, indivisible spheres. According to Dalton's model, atoms of each element are identical to each other in mass and all other properties, while atoms of one element differed from atoms of each other element. Dalton's model could explain most of what was known about the chemistry of atoms and molecules for nearly a hundred years.

Figure 12.13 Dalton proposed that atoms were the smallest particles that make up matter and that they were indestructible. With his model, Dalton could predict most of what was known about chemistry at the time.

The Dalton model of the atom was replaced when J.J. Thomson established in 1897 that the atom was divisible. He discovered that the "cathode rays" in gas discharge tubes (see Figure 12.14) were negatively charged particles with a mass nearly 2000 times smaller than a hydrogen atom, the smallest known atom. These negatively charged particles, later named "electrons," appeared to have come off the metal atoms in one of the electrodes in the gas discharge tubes. Based on this new information, Thomson developed another model of the atom, which consisted of a positively charged sphere with the negatively charged electrons imbedded in it, as illustrated in Figure 12.15.

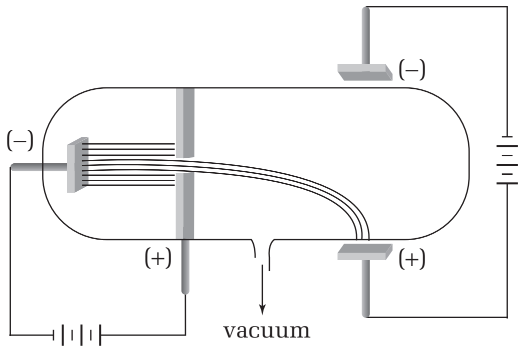

Figure 12.14 Metal electrodes were sealed in a glass tube that had been evacuated of all but a trace of a gas. A potential difference was created between the two electrodes. "Cathode rays" emanated from the negative electrode and a few passed through a hole in the positive electrode. Thomson showed that these "cathode rays" carried a negative charge by placing another set of electrodes outside the tube. The positive plate attracted the "rays."

Even as Thomson was developing his model of the atom, Ernest Rutherford (1871–1937) was beginning a series of experiments that would lead to replacement of Thomson's model. Rutherford was born and educated in New Zealand. In 1895, he went to England to continue his studies in the laboratory of J.J. Thomson. While there, he became interested in radioactivity and characterized the "rays" emitted by uranium, naming them "alpha rays" and "beta rays." He discovered that alpha rays were actually positively charged particles.

In 1898, Rutherford accepted a position in physics at McGill University in Montréal, where he continued his studies of alpha particles and published 80 scientific papers. Nine years later, Rutherford returned to England, where he accepted a position at the University of Manchester.

While in Manchester, Rutherford and his research assistant Hans Geiger (1882–1945) designed an apparatus (see Figure 12.16) to study the bombardment of very thin gold foils by highly energetic alpha particles. If Thomson's model of the atom was correct, the alpha particles would pass straight through, with little or no deflection. In their preliminary observations, most of the alpha particles did, in fact, pass straight through the gold foil. However, in a matter of days, Geiger excitedly went to Rutherford with the news that they had observed some alpha particles scatter at an angle greater than 90°. Rutherford's famous response was, "It was quite the most incredible event that has ever happened to me in my life. It was almost as incredible as if you fired a 15 inch shell at a piece of tissue paper and it come back and hit you!" The observations were consistent: Approximately 1 in every 20 000 alpha particles was deflected more than 90°. These results could not be explained by Thomson's model of the atom.

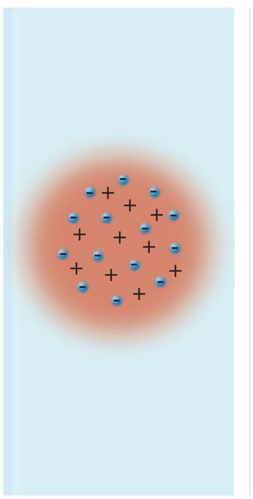

Figure 12.15 Thomson named his model the "plum pudding model" because it resembled a pudding with raisins distributed throughout.

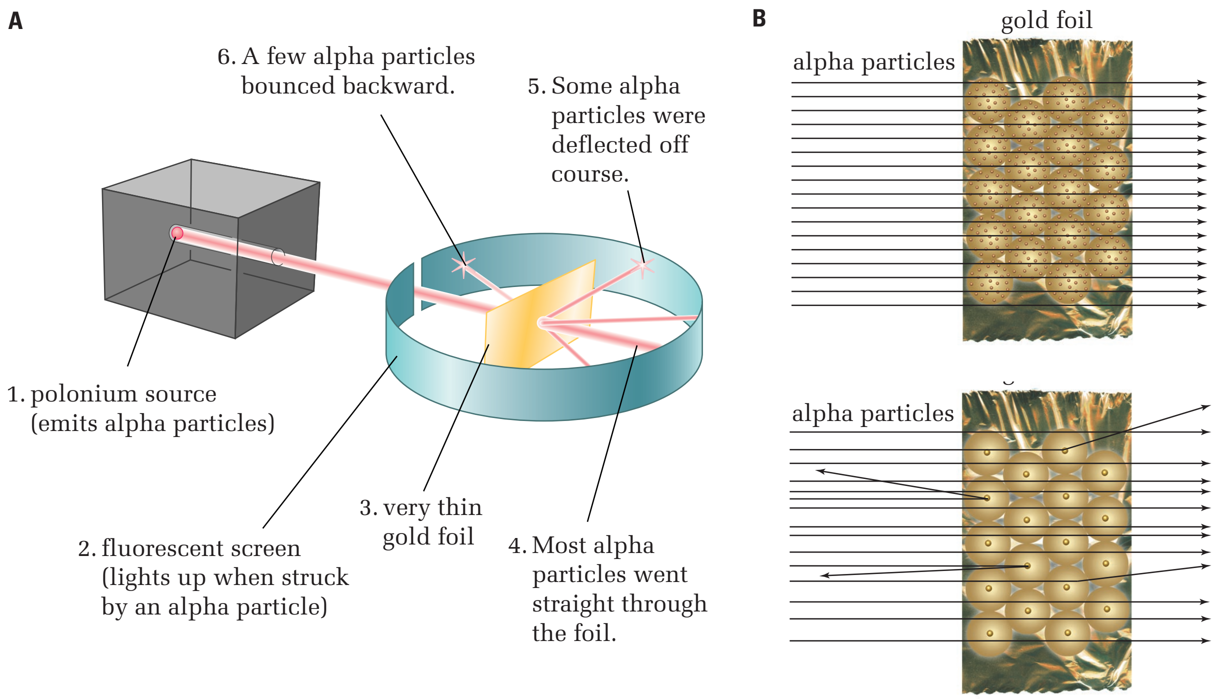

Figure 12.16 **(A)** A fine beam of alpha particles was directed at a very thin gold foil. The circular screen around the foil was coated with zinc sulfide, which emitted a flash of light when hit by an alpha particle. **(B)** If positive and negative charges were equally distributed throughout the foil, they would have little effect on the direction of the alpha particles. **(C)** If all of the positive charge in each atom was concentrated in a very tiny point, it would create a large electric field close to the point. The field would deflect alpha particles that are moving directly toward or very close to the tiny area where the positive charge is located.

What force could possibly be strong enough to repel such a highly energetic alpha particle? Rutherford searched his mind and performed many calculations. He concluded that the only force great enough to repel the alpha particles would be an extremely strong electrostatic field. The only way that a field this strong could exist was if all of the positive charge was confined in an extremely small space at the centre of the atom. Thus, Rutherford proposed his **nuclear model** of the atom. All of the positive charge and nearly all of the mass of an atom is concentrated in a very small area at the centre of the atom, while the negatively charged electrons circulate around this "nucleus," somewhat like planets around the Sun, as illustrated in Figure 12.17.

In the following Quick Lab, you will apply some of the same concepts that Rutherford used to estimate the size of the atomic nucleus.

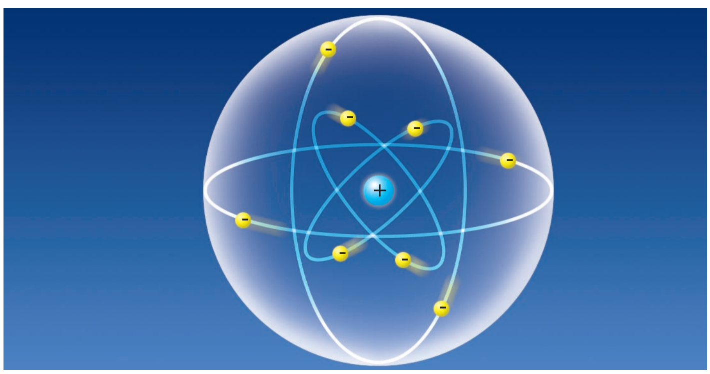

Figure 12.17 Rutherford's nuclear model resembles a solar system in which the positively charged nucleus could be likened to the Sun and the electrons are like planets orbiting the Sun.